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MHD Shocks in the ISM

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We survey shock solutions of a partially ionized gas with a magnetic field. The gas is modeled by interacting neutral, ion, electron and charged grain components. We employ a small neutral-ion chemical network to follow the dissociation and ionization of the major species. Cooling by molecular hydrogen (rotational, vibrational and dissociation), grains and dipole molecules is included. There are three basic types of solutions (C, C*, and J) and some more complicated flows involving combinations of the basic types. The initial preshock conditions cover hydrogen nuclei densities of $1 < n < 10^{10} \text{ cm}^{-3}$ and shock velocities of $5 < v_s < 60 \text{ km/s}$. The magnetic field is varied over 5 decades and the sensitivity of the results to grain parameters, UV and cosmic ray fluxes is ascertained.

The parameter space is quite complicated, but there exist some simple divisions. When the initial ionization fraction is small ($x_i < 10^{-5}$), there is a sharp transition between fully C solutions at low velocity and strong J solutions at high velocity. When the initial ionization fraction is larger, C* and/or very weak J shocks are present at low velocities in addition to the C solutions. The flow again changes to strong J shocks at high velocities. When the ionization fraction is large and the flow is only slightly greater than the bulk Alfvén velocity, there is a complicated mixture of C, C* and J solutions.

1 INTRODUCTION

In the interstellar medium, shocked, partially ionized gas behaves as weakly coupled neutral and charged fluids (Mullan 1971, Draine 1980, Draine and Roberge 1982, Chernoff, Hollenbach and McKee 1982, Chernoff 1987, Chernoff and McKee 1988, Chernoff, Hollenbach and McKee 1989). Previously, detailed MHD calculations have been limited to a particular class of solutions (the "C" type, Chernoff, Hollenbach and McKee 1982, Draine and Roberge 1982) or have focused on a few illustrative special cases (Draine 1980). Here we report a survey of MHD multifluid models of interstellar shocks and sketch an overall picture of the gas' behavior, sacrificing the detail necessary to produce accurate line ratios and line

intensities. Elsewhere, we focus on more accurate and detailed calculation of specific cases.

The general categorization of shock solution was discussed by Chernoff (1987). For simple cooling and ionization laws, there exist three basic sorts of solutions: C, C* and J. C solutions are completely continuous and the neutral gas is everywhere supersonic. J solutions have regions of subsonic neutral flow *with a viscous subshock*. The location of the subshock and its strength is determined by the condition that the flow be able to pass through a downstream critical point. C* solutions are completely continuous but the neutral gas heats up sufficiently (by ion-neutral friction) to become subsonic without a subshock. Solutions tend to be C when the ratio of radiative cooling to collisional heating is large and/or when the Alfvén Mach number of the neutral flow is low. Apparently, there is no guarantee that only a single time-independent solution exists for given preshock conditions. The present study includes some examples of multiple solutions and also of solutions more complicated than the three basic types. One of the virtues of the solution technique introduced by Chernoff (1987) is that all possible solutions may be found.

For the models discussed in this paper we assume that the ionization fraction is determined by balancing ionization (electron, ion and neutral collisional ionization rates plus cosmic ray rates) and recombination processes (atomic and molecular rates) at each point in the flow. We integrate the chemistry and follow the molecular versus atomic hydrogen composition of the gas. We have used realistic cooling functions for molecular hydrogen describing the rotational, vibrational (Hollenbach and McKee 1979) and dissociation processes (Hollenbach and McKee 1988). The neutral heating by ion collisions and drifting grains (using Draine's steady state solution for the grain motion, 1980) includes the most important heating effects. In addition, the temperatures of the ion and electron components are calculated using all the most important heating and cooling processes (collisional heating by the neutrals, radiative cooling by excitation of atomic and molecular transitions in the neutrals and heating by collisionless plasma instability).

Illustrative and *tentative* results are presented in the accompanying table (additional ones are included with the poster). The initial condition are the preshock hydrogen nuclei density (abscissa) and shock velocity (ordinate). The gas is completely molecular upstream. The magnetic field is given as $B = 10^{-6} n^{1/2} b$ G. for $b = 0.1$. (Other values of b are shown with the poster). The external ionization rate is $\zeta = 10^{-15}$ per nuclei per sec. A generic dipole coolant with abundance $x_d = 10^{-4}$ is present. The grains are 1% by mass, with density $\rho_{gr} = 2.5$ gm/cm³ and radius $a_{gr} = 10^{-5}$ cm. The solutions are labeled C, * (meaning C*) and J. 'None' means the algorithm failed to converge, but is not otherwise meaningful. The temperature contour of $T = 30000$ K is illustrated. To the right of that contour all solutions are strong J shocks. To the left, solutions are either C, C* or very weak J shocks. Detailed distinctions between solutions at low velocity (Alfvén Mach numbers of a few) are not represented because the 5 km/s intervals are not sufficiently fine to resolve such variations. Significant dissociation occurs to the right of the temperature contour and the viscous subshocks have compression ratios of close to 4.

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